

University of Washington
Seattle, WA 98195
Grant NAG 5-1255

GRANT
IN-89-CR
177567
P. 10

Final Report on Grant NAG 5-1255
Determination of Nitrogen to Carbon Abundance Ratios from
Transition Layer Emission Lines
Grant Period September 1990-August 1992
Principle Investigator: Erika Böhm-Vitense

I. Introduction

We have finished studying the nitrogen to carbon abundance ratios for stars with different effective temperatures T_{eff} and luminosities using transition layer emission lines and using spectra available in the IUE archives.

Past studies of transition layer emission lines have shown that for solar abundance stars the ratios of emission line strengths are always nearly the same. If emission measures $Em = \int_{h_1}^{h_2} n_e^2 dh$ are derived for a given star for emission lines originating in layers between different heights h_1 and h_2 with different temperatures they follow a power law $Em(T) = E \times T^{-\alpha}$ where $\alpha = 1.2 \pm 0.3$. Using the ratio of the CIV and CII emission line fluxes at 1550 Å and 1335 Å, which is independent of the carbon abundance, the exponent α can be determined. Using either of the two lines the constant E can be derived which is, however, proportional to the carbon abundance. The emission measures as a function of temperature are thus known except for the factor of the carbon abundance $A(C)$. Emission line strengths for other lines of other elements are proportional to their abundances $A(\text{element})$ and the emission measures Em . With the known $Em(T) \times A(C)$ the abundance ratios relative to carbon can be determined.

The use of transition layer emission lines of CIV and NV limits our studies to those stars which show these emission lines, which means to stars situated in the HR diagram between the Cepheid instability strip (which agrees with the boundary line for efficient convection zones, Böhm-Vitense and Dettmann 1980) and the Linsky-Haisch (1979) boundary line for the existence of coronae and high temperature transition layers. For supergiants this limits our study to G stars. For giants and subgiants we can study F, G, and K stars. Our studies therefore concentrated on giants and subgiants.

II. The Giants

For these stars we expect to see evolutionary increases in the N/C abundance ratios when they evolve from the higher temperature ($T_{\text{eff}} \sim 7000\text{K}$) F stars to the lower temperature G and K ($T_{\text{eff}} \sim 4500\text{K}$) stars with increasingly deeper convection zones. For the K stars this

(NASA-CR-191921) DETERMINATION OF
NITROGEN TO CARBON ABUNDANCE RATIOS
FROM TRANSITION LAYER EMISSION
LINES Final Report, Sep. 1990 -
Aug. 1992 (Washington Univ.) 10 p

N94-19421

Unclas

NSIIF

leads to deep mixing bringing up material which has gone through an incomplete C N nuclear processing chain leading to a conversion of carbon to nitrogen. For these stars increases in the N/C abundance ratios were determined from groundbased observations (Lambert and Ries 1982), confirming theoretical expectations qualitatively, however, larger than expected values were found indicating deeper mixing than calculated. These authors used molecular bands observed in absorption. Molecule formation is very temperature sensitive. Molecules form mainly in high photospheric layers with the lowest temperatures. Unfortunately the temperature minimum for these stars is rather uncertain. It therefore seems important to verify these results with an independent method. Molecular bands strong enough for abundance analysis for giants are observable only for K and late G giants. For increasing temperatures they become too weak to permit quantitative analysis. Lambert and Ries could therefore not determine for which T_{eff} the N/C enrichment starts. This is especially interesting because it gives us information at which state of evolution the convection zone reaches the layer in which C N nuclear processing has occurred. For the G and F giants only high excitation atomic absorption lines of carbon and nitrogen can be observed from the ground. These are subject to non-local-thermodynamic equilibrium effects (NLTE) which cannot yet be assessed accurately. CI and CII lines often give discordant results. Abundance studies from transition layer emission lines can help out.

In our previous report we described how our method works and showed that within the limits of error for both kinds of studies our results agree well with groundbased observations for targets which have been studied by both methods. We also reported our main results for the giants, which we show again in Figure 1. We find general agreement with theoretical expectations, though for several K giants higher than expected N/C abundance ratios are also found by us (Böhm-Vitense and Mena-Werth 1992). It also appeared that the increase in the N/C abundance ratio occurs for somewhat higher temperatures, which means earlier than expected theoretically, indicating that convective mixing reaches deeper than calculated. This may indicate either that convective energy transport is more efficient than assumed in the calculations or that convective overshoot at the bottom of the convection zone extends mixing to deeper layers.

Another interesting result was obtained during the course of these studies: For several F giants we find an unexpected increase in the N/C and/or Si/C abundance ratios. Deep mixing should occur only for K and perhaps late G giants, not for F giants. We followed up on this anomaly. When during C N nuclear reactions carbon is transformed into nitrogen the carbon abundance decreases. Since the sum of the carbon and nitrogen abundance remains constant we can calculate the change in the carbon abundance $\Delta \log C$, for the observed increase in the N/C abundance ratio. This leads to an increase in the Si/C abundance ratio. From the ratio of the Si IV line flux at 1393 Å to the CIV line flux we can check this abundance ratio. We found several F giants which had larger than expected Si/C abundance ratios. For some of these stars we attributed this to a larger Si surface abundance as observed for Ap stars and attributed there to radiative diffusion. The Si enriched F giants are then presumably

descendents of Ap stars. For other F giants we find increases in the N/C abundance ratio *and* in the Si/C abundance ratio of nearly equal amounts. We attribute these anomalies to a surface carbon deficiency as seen in Am stars again attributed to diffusion. We conclude that these stars are descendents of Am stars. If these assertions are correct then the anomalies must disappear when convection reaches deep enough to wipe out the abundance gradients caused by diffusion. In a follow up study we did indeed find that these abundance anomalies disappear for the G giants. This gives information about both the depth of the convection zone for G0 giants and for the depth over which diffusive separation worked during the main sequence lifetime of these stars.

An unexplained enhancement in the Si/C abundance ratios occurs for some K giants when the results of deep mixing are seen. A similar enrichment in Si is seen for population II giants. Such an enhancement in the Si/C abundance ratio is not seen in any of the RS CVn stars observed so far.

III. The Supergiants

We have now extended our studies to supergiants, subgiants and also main sequence stars. As discussed above for supergiants the available spectral range is limited to G stars. There are only four G supergiants for which the exposures were long enough such that the NV line could be measured with confidence. The stars are listed in Table 1. These stars have previously been studied by Luck and Lambert (1981) by means of groundbased observations, using the high excitation CI and NI lines. These authors found higher N/C abundance ratios than are compatible with theoretical expectations. Additional mixing is required. Since the high excitation lines are vulnerable to NLTE effects, as mentioned above, there was some suspicion that perhaps the observationally derived large N/C ratios might be in error. Our studies of the transition layer emission lines confirmed, however, the high N/C abundance ratios (Mena-Werth 1992) thereby confirming that deeper mixing occurs in these stars than expected from standard evolution theory. In Table 2 we give the N/C abundance ratios for the four supergiants as found from ground based observations and as found by Mena-Werth (1992).

Table 1
Stellar Data for Supergiants

Star	HD Number	Spec. Class	V	B-V	E(B-V)	M_v
δ TrA	145544	G2Ib-IIa	3.85	1.11	0.28	—
β Dra	159181	G2Ib-IIa	2.79	0.98	0.15	—5.2
β Aqr	204867	G0Ib	2.91	0.83	0.07	—4.7
α Aqr	209750	G2Ib	2.96	0.98	0.12	—5.3

Table 2
Abundance and Surface Flux Ratios for Supergiants
from Mena-Werth (1992)

Star	$\Delta \log N/C^a$	$\Delta \log N/C^b$	$F(CIV)/F(CII)$	$\Delta \log N/C^c$ for $Em \propto T^{-1.2}$
δ TrA	0.75	—	1.17	0.72
β Dra	0.43	0.77	2.28	0.53
β Aqr	0.66	0.83	1.40	0.69
α Aqr	0.83	0.94	0.94	0.81

^aNitrogen to carbon abundance ratios with respect to the sun calculated in this work.

^bNitrogen to carbon abundance ratios with respect to the sun calculated in Luck and Lambert (1985).

^cNitrogen to carbon abundance ratios with respect to the sun calculated with $Em \propto T^{-1.2}$ through the CIV emission line point.

For these supergiants we find rather large variations in the CIV/CII line flux ratios leading to different temperature dependences of the emission measures. We therefore also checked what we would find assuming $Em(T) \propto T^{-1.2}$ as is found on average for most stars. This leads to only minor changes in the abundance ratios as seen in the last column of Table 1. β Dra, a very active star, is the only star for which our result deviates from the groundbased results. It is also the star with the highest CIV/CII line flux ratio. We wonder whether some of the CIV line flux seen is not due to the transition layer but perhaps due to some circumstellar material.

Theoretical studies (Becker and Cox 1982) have shown that the high N/C problem can be overcome by more extended mixing above the convective cores of massive main sequence stars, the progenitors of the supergiants. This may be due to convective overshoot. Our studies are another important argument in favor of this additional mixing, supporting other arguments coming from lower Cepheid masses and from discussions of color magnitude diagrams in the LMC (Chiosi *et al.* 1992).

IV. Luminosity Class IV Stars

In Figure 2 the results of our $\log N/C$ abundance ratio determinations are shown. For $\log T_{\text{eff}} < 3.75$ the values scatter around 0 with deviations of about ± 0.2 as expected from our error estimates. The only exception is the F2 V star 26 Boo, a member of the Hyades moving group. The measurement was, however, judged to be uncertain. Proceeding to lower T_{eff} the star ζ Her with $\log T_{\text{eff}} = 3.763$ is the first star with a high N/C abundance ratio. ζ Her is a G0 IV variable star with low rotation velocity ($v \sin i = 2.9$ km/s). For the more

rapidly rotating, chromospherically active stars the increase in $\log N/C$ occurs apparently for somewhat lower T_{eff} , namely for $\log T_{\text{eff}} \leq 3.76$. For T_{eff} lower than that no stars with solar N/C are found and also no stars with $v \sin i > 3$ km/s. This is in qualitative agreement with our suggestion (Böhm-Vitense 1991) that deep mixing, as indicated by the high N/C abundance ratios, leads to a decrease in the surface rotation velocities. More observations are needed to clarify how close this relation actually is and whether another explanation is also possible.

Theoretically mixing deep enough to bring nuclear processed material to the surface should occur only for $\log T_{\text{eff}} < 3.71$. Our observations show that it occurs already for somewhat higher T_{eff} namely for $\log T_{\text{eff}} \leq 3.76$. Either the surface convection reaches deeper than calculated or the nuclear processed material is mixed out further than we think by some unknown mixing process which may perhaps be more effective for slowly rotating stars.

V. Luminosity Class V Stars

For main sequence stars we generally expect solar N/C abundance ratios. For F and G stars the convection zones are shallow. For later spectral typed with deep convection zones the interior temperatures are not high enough even for the beginning of the operation of the C N cycle.

We have studied all main sequence star spectra for which the carbon and nitrogen emission line fluxes could be measured with confidence. We also included some stars for which the fluxes were rather uncertain. For main sequence G stars the situation is rather bad. The emission lines are weak and the exposure times are not long enough to show well defined emission lines. Measurements for the N V line fluxes reported by different authors for the same star and often measured on the same spectra frequently differ by up to a factor of 2. For the K stars the situation is somewhat better but not good either. We therefore expect rather large uncertainties for the N/C abundance ratios determined for these stars. Figure 3 shows the measured values. For most values which are considered to be “certain” the scatter around 0 is within the original error estimate of $\sigma \leq \pm 0.27$ in $\Delta \log N/C$ with only a few exceptions. For the uncertain values the scatter is three times as large, which may be expected. Unexpected is that the average value for the “certain” measurements yields $\Delta \log N/C \sim 0.12$. Is the main sequence abundance value actually that much higher than our assumed value of $\log N/C = 0.5$? The measurements for the giants and subgiants do not support that conclusion. We rather think that for weak lines we tend to measure too high values for the emission line fluxes, because we tend to include noise peaks which for weak lines and noisy spectra can have a fairly large influence. We will not include noise dips. As expected we do not see a systematic change of the N/C abundance ratios with temperature for the “certain” values.

VI. Summary

a. Abundance Studies

In conclusion we can say that the N/C abundance ratio determinations using transition layer emission lines are as accurate as the photospheric abundance determinations as found by comparison of results obtained by both methods for the same stars. Our measurements confirm photospheric abundance determinations in regions of the HR diagram where they can be obtained. Our studies have extended the temperature range to higher temperatures. They have shown the exact positions in the HR diagram where the mixing due to the outer convection zones reaches deep enough to bring nuclear processed material to the surface. This occurs at effective temperatures which are higher by $\Delta \log T_{\text{eff}} \sim 0.04$ or roughly 400K than expected theoretically. Since the depth of the convection zone increases rapidly with decreasing T_{eff} this may indicate considerable overshoot beyond the lower boundary of the convection zone.

Our N/C abundance ratio determinations from transition layer emission lines have confirmed that the actual enrichment observed for some cool giants is larger than expected theoretically, again indicating a larger degree of mixing in several stars either from below or from above. For the supergiants it probably indicates overshoot above the convective core in the progenitor main sequence stars. For the more massive giants this may also be the case, though we did not find a correlation between $\Delta \log \text{N/C}$ and the absolute magnitudes, but these are rather uncertain.

As byproducts of these studies we also found anomalies in Si/C and N/C abundance ratios for F giants which can be understood as the relict of surface abundance changes for their main sequence progenitors due to diffusion. This anomaly disappears for G giants, for which the depths of the convection zones are apparently deep enough to wipe out these element separations (Böhm-Vitense 1992).

We also found a slight increase of the Si/C abundance ratio for some cool population I giants which resembles the increase in the Si/C abundance ratio found in population II giants. This unexpected and unexplained result deserves further study.

b. By-products of this Investigation

In the course of our abundance studies we have to determine the line flux ratio for the CIV and CII lines. We detected a systematic increase of the CIV/CII line flux ratio with increasing rotational velocities (Böhm-Vitense and Mena-Werth 1991). Since larger rotational velocities are believed to be correlated with larger magnetic activity and since changing CIV/CII emission line flux ratios indicate a change in heating mechanism (Böhm-Vitense 1987) this actually shows a change in the importance of different heating mechanisms for stars with or without large magnetic activity.

It was also discovered that the T_{eff} for which deep mixing occurs, as indicated by the increase in the N/C abundance ratio, agrees with the T_{eff} for which the maximum rotational velocity for single stars decreases steeply, see Figure 1. We suspect that the decrease in

rotational velocity is due to downward transport of angular momentum by convection, which establishes a depth independent specific angular momentum (Endal and Sofia 1979; Böhm-Vitense 1991). We fail to see how braking by stellar winds (Gray 1991) can achieve such a rapid braking, especially since coronal X-ray emission, which may be expected to increase with strong stellar winds, decreases at this point in the HR diagram.

References

- Becker, S. A. and Cox, A. N. 1982, *ApJ*, 260, 707
Bertelli, G., Bressan, A., Chiosi, C., and Angerer, K. 1986, *A & AS*, 66, 191
Böhm-Vitense, E., and Dettmann, T. 1980, *ApJ*, 236, 560
Böhm-Vitense, E. 1987, *ApJ*, 317, 750
Böhm-Vitense, E. 1991, *AJ*, 103, 608
Böhm-Vitense, E. 1992, *ApJ*, submitted
Böhm-Vitense, E. and Mena-Werth, J. 1991, *ApJ*, 378, 718
Böhm-Vitense, E. and Mena-Werth, J. 1992, *ApJ*, 390, 253
Chiosi, C., Wood, P. R., Bertelli, G., Bressan, A. and Mateo, M. 1992, *ApJ*, 385, 205
Endal, A. S. and Sofia, S., 1979, *ApJ*, 232, 531
Gray, D. 1991, Conference proceeding, Noto conference
Lambert, D. and Ries, L. M. 1981, *ApJ*, 248, 228
Linsky, J. and Haisch, B. M. 1979, *ApJ*, 229, L27
Luck, R. E. and Lambert, D. L. 1981, *ApJ*, 245, 1018
Mena-Werth, J. 1992, Thesis, University of Washington
Sweigart, A. V., Greggio, L. and Renzini, A. 1989, *ApJS*, 69, 911

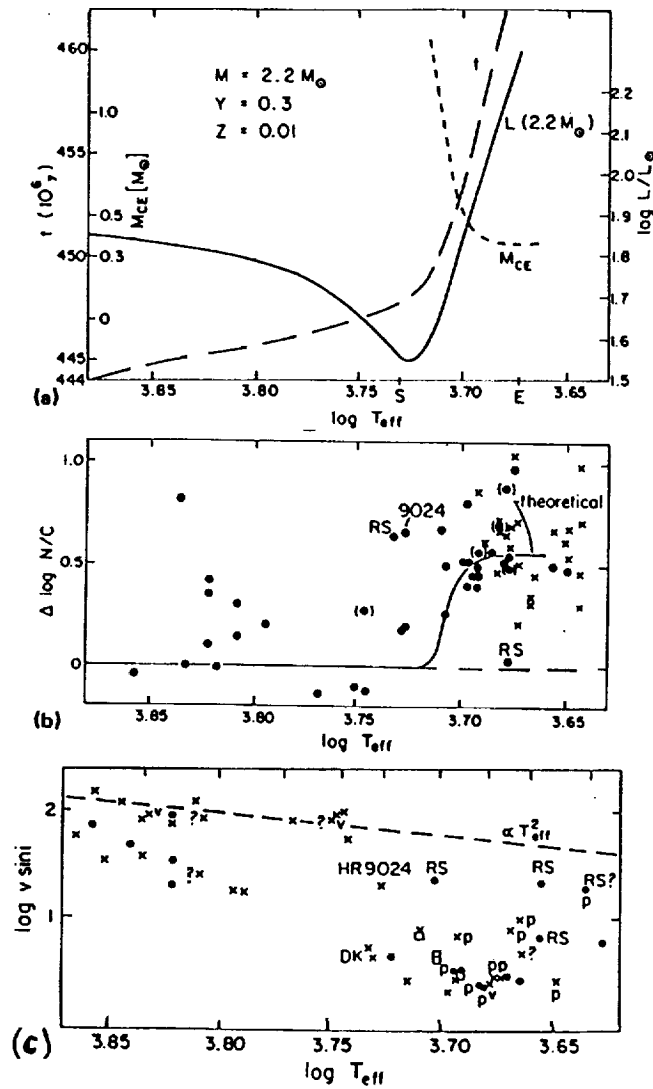


Figure 1. (a) The theoretical evolutionary track of a $2.2 M_{\odot}$ star is shown in the T_{eff} , luminosity diagram (right-hand scale). Also plotted is the age t as a function of T_{eff} (left-hand outer scale) and the depth of the convection zone, measured by the mass M_{CE} [M_{\odot}] (left-hand inner scale) below the lower boundary of the convection zone. The point E gives the evolutionary phase with the largest depth (in mass) of the convection zone. Data are from Sweigart *et al.* (1989). (b) The observed changes in abundance ratios of nitrogen to carbon N/C , as compared to main sequence abundances, are plotted as a function of T_{eff} . The point for the δ Scuti star β Cas at $\log T_{\text{eff}} \sim 3.86$ lies at $\Delta \log N/C = -0.24$. (c) The rotational velocities $v \sin i$ for the program stars are plotted as a function of the effective temperatures. The maximum observed $v \sin i$ decrease at the same point where the N/C abundance ratios change.

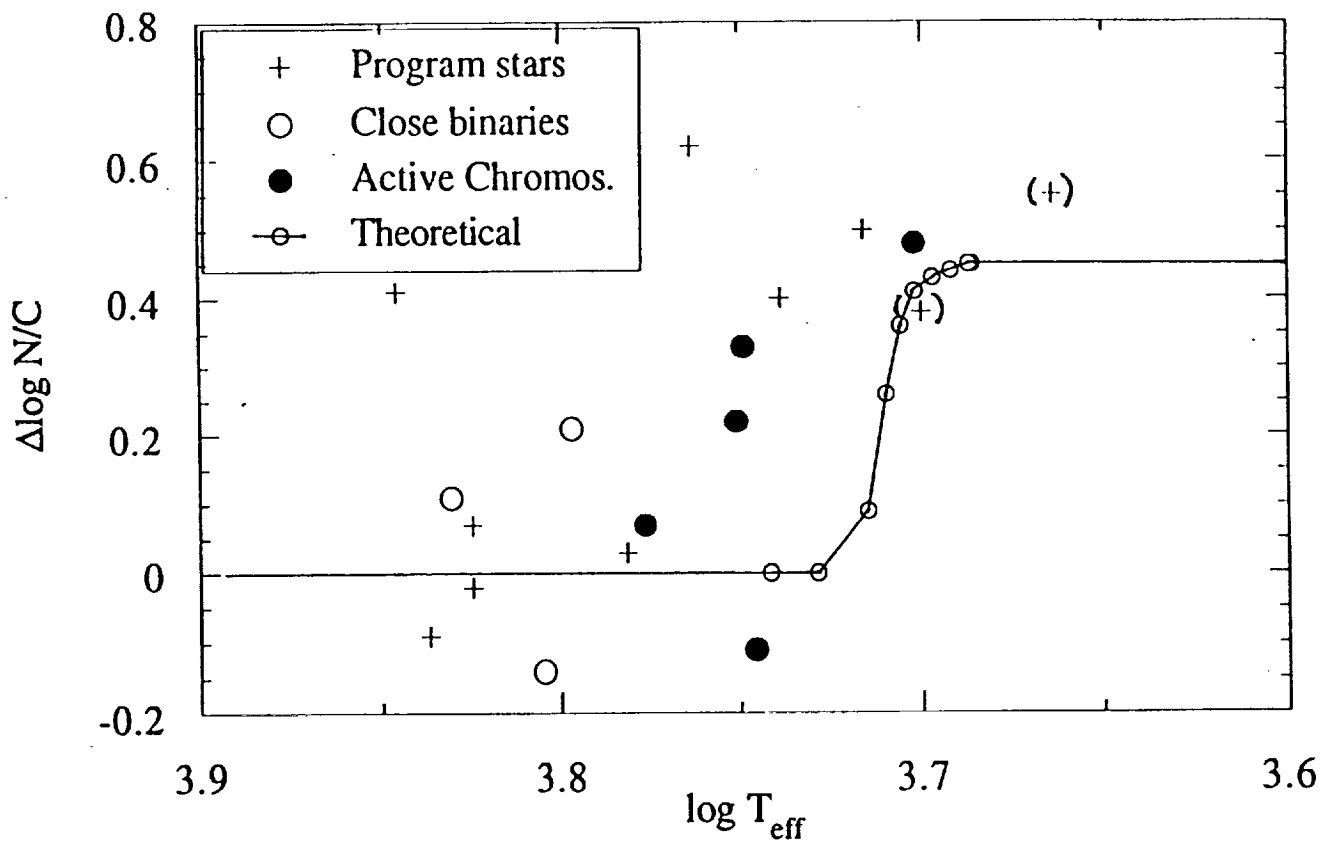


Figure 2. The excess abundance ratios $\Delta \log N/C$ for subgiants are plotted as a function of $\log T_{\text{eff}}$. The symbols are explained in the figure. From Mena-Werth (1992). The observed increase in the N/C abundance ratios occurs at higher temperatures than expected theoretically.

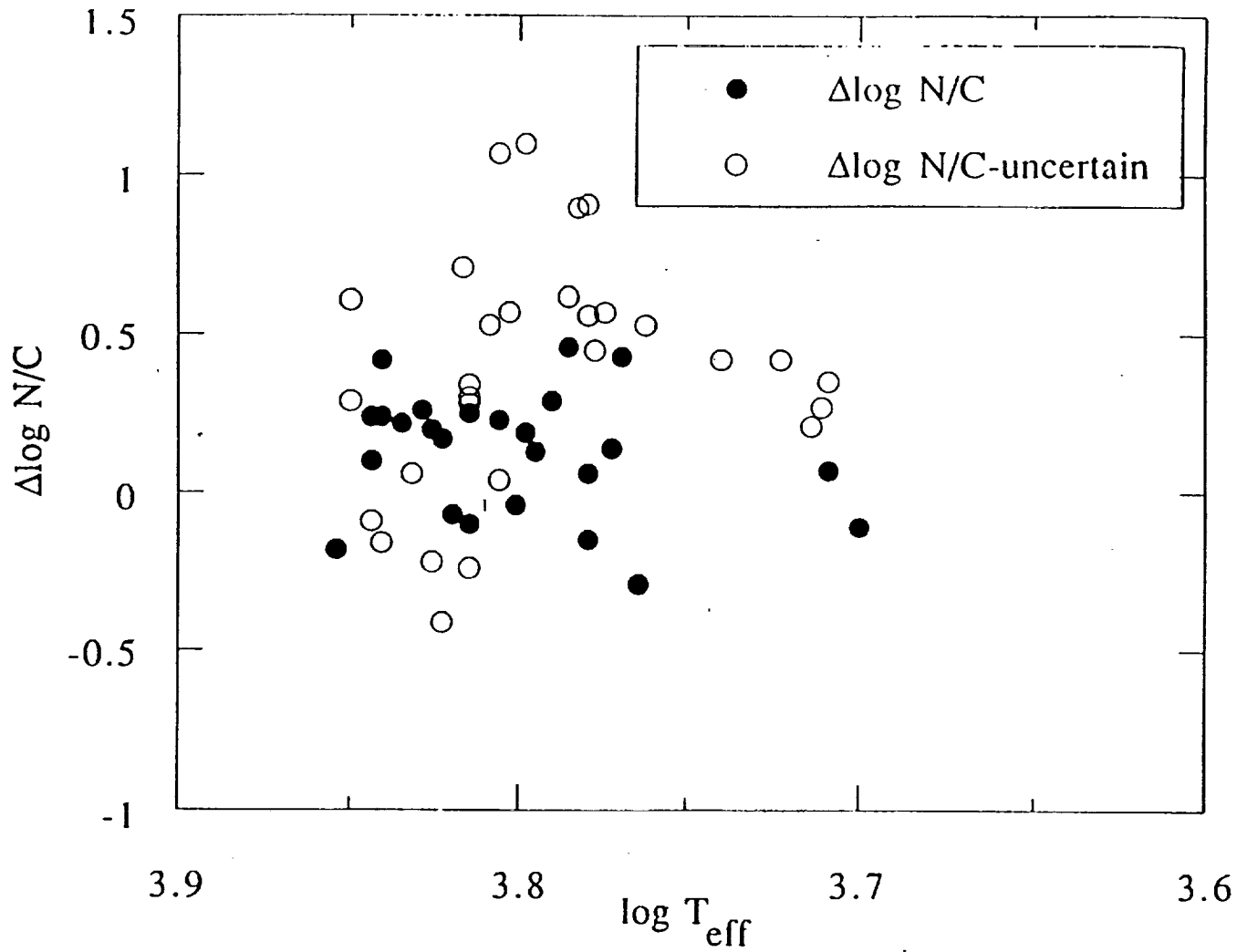


Figure 3. The excess abundance ratios $\Delta \log N/C$ for luminosity class V stars are plotted as a function of $\log T_{\text{eff}}$. Symbols as explained in the Figure. From Mena-Werth (1992).